SEISMOLOGY OF THE MOON AND IMPLICATIONS ON INTERNAL STRUCTURE, ORIGIN AND EVOLUTION*

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1. Introduction

The objective of the passive seismic experiment is to measure vibrations of the lunar surface produced by all natural and artificial sources of seismic energy and to use these data to deduce the internal structure and constitution of the Moon, the nature of tectonic processes which may be active within the Moon, the rate of strain energy release for the lunar body, and the numbers and masses of meteroroids striking the lunar surface. The instrument used is also capable of measuring changes in gravity and tidal tilts which occur in its vicinity. To accomplish these objectives, seismic data must be combined with data from laboratory measurements of the physical and chemical properties of surface rocks, and many other geophysical and geochemical measurements. Thus far, we have had the opportunity to record data from two lunar seismic stations which were installed by the astronauts during Apollo missions 11 and 12. The combined recording time from these stations is presently over 9 months, but there was no overlap to permit recording the same event at two stations. Results from the analysis of these data have been presented by the seismic experiment team in five previous papers [1, 2, 3, 4, 5].

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To apply seismic methods as they are applied on Earth would require several stations in operation at the same time. In fact, approximately 30 stations on the near side of the Moon would be required to achieve a station density comparable with that on Earth. Nevertheless, even with data from only 2 stations, we can deduce a few basic facts about the meteoroid flux and the dynamics and structure of the Moon.

The Apollo seismic station contains 4 seismometers. Three of them form a matched triaxial set with natural periods of 15 sec. The fourth is sensitive to vertical motion and has a natural period of 1 sec. The instruments can detect motions of the lunar surface as small as 1 Å. The instrument can respond to a series of 15 commands sent from Earth, which control such functions as sensitivity, calibration, thermal state, frequency characteristics, leveling and centering of the seismometers.

Seismometers are quite temperature-sensitive, and must, therefore, be protected from the extreme temperature variations which occur at the lunar surface. The combination of a thermal shroud made of sheets of aluminized mylar and a small heater serves this purpose. The instrument weighs 22 lbs. and is constructed principally of beryllium.

The Apollo 11 version of the instrument used solar panels for power and the seismic sensors were incorporated in the central station in order to reduce requirements on astronaut time. The use of solar-cell power, instead of the nuclear battery used in the Apollo 12 station, limited operation to the lunar day. The station was installed about 16.8 m from the nearest footpad of the LM. The LM was the source of a wide variety of periodic and random noises, which interfered seriously with identification of proper seismic signals. This instrument functioned for 21 d during July and August, 1969, before operation was terminated by failure of the command receiving system.

Figure 1 shows the Apollo 12 instrument as installed on the lunar surface in November 1969. This instrument continues to function, except for the short period seismometer which became inoperative, apparently from damage during transit to the Moon.

Early in the Apollo 11 mission, we discovered that the true background seismic noise level on the Moon is extremely low, even below the measurement capability of the instrument. There is no sustained motion of the lunar surface analogous to microseisms on Earth, detectable with the present instruments. Thus, seismometers can be usefully operated on the lunar surface at 100 to 1000 times greater sensitivity than on Earth. The Apollo 12 seismometers are presently operating at a magnification of 10 million at a period of two seconds. This is a very favorable factor for seismic exploration of the Moon.

Approximately 250 signals believed to be of natural origin have been identified on the records from the Apollo 11 station and from the first seven months of operation of the Apollo 12 stations. Signals from two artificial impacts at accurately known times and distances from the seismometers, have also been recorded – the impacts of the Apollo 12 LM ascent stage and of the third stage (S-IVB) of the Apollo 13 Saturn booster. These two known impacts were necessary keys to the study of lunar seismology, because the records for them are utterly different from any obtained in observations on Earth.

The locations of the Apollo 12 seismic station and the impact points are shown in Figure 2. The LM struck the lunar surface 73 km from the station at a velocity of 1.68 km/sec and at an inclination of its path to the Moon surface of only 3.7°. Motion was toward the station at the time of impact, leading to some speculation that pro-

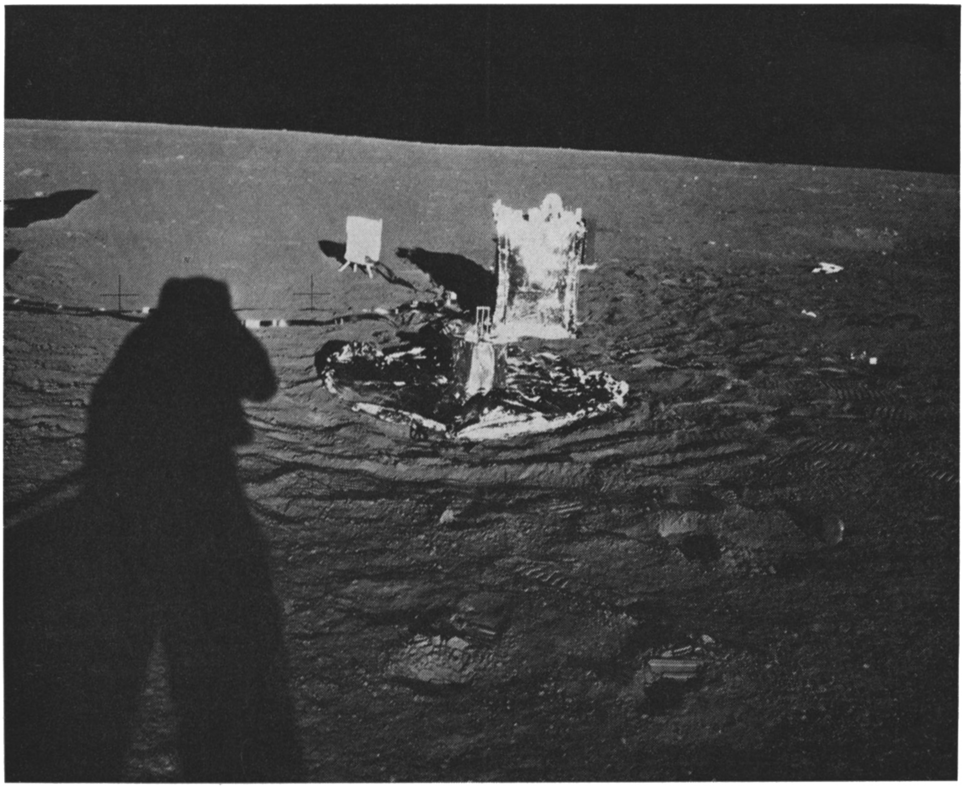

Fig. 1. Apollo 12 seismic station installed on the lunar surface.

longation of the seismic signal may have resulted from impacts of ejecta. The equivalent kinetic energy of the LM impact was 0.8 metric tons of TNT. The S-IVB struck the surface at nearly normal incidence, 135 km from the station, with a velocity of 2.58 km/sec, heading toward the northeast. The equivalent kinetic energy release of this impact was 11.1 metric tons of TNT.

The region of the impacts is located in the southeastern part (near the edge) of Oceanus Procellarum. The relatively smooth area, particularly between the LM impact point and the station, is believed to be igneous rock which entered the region as

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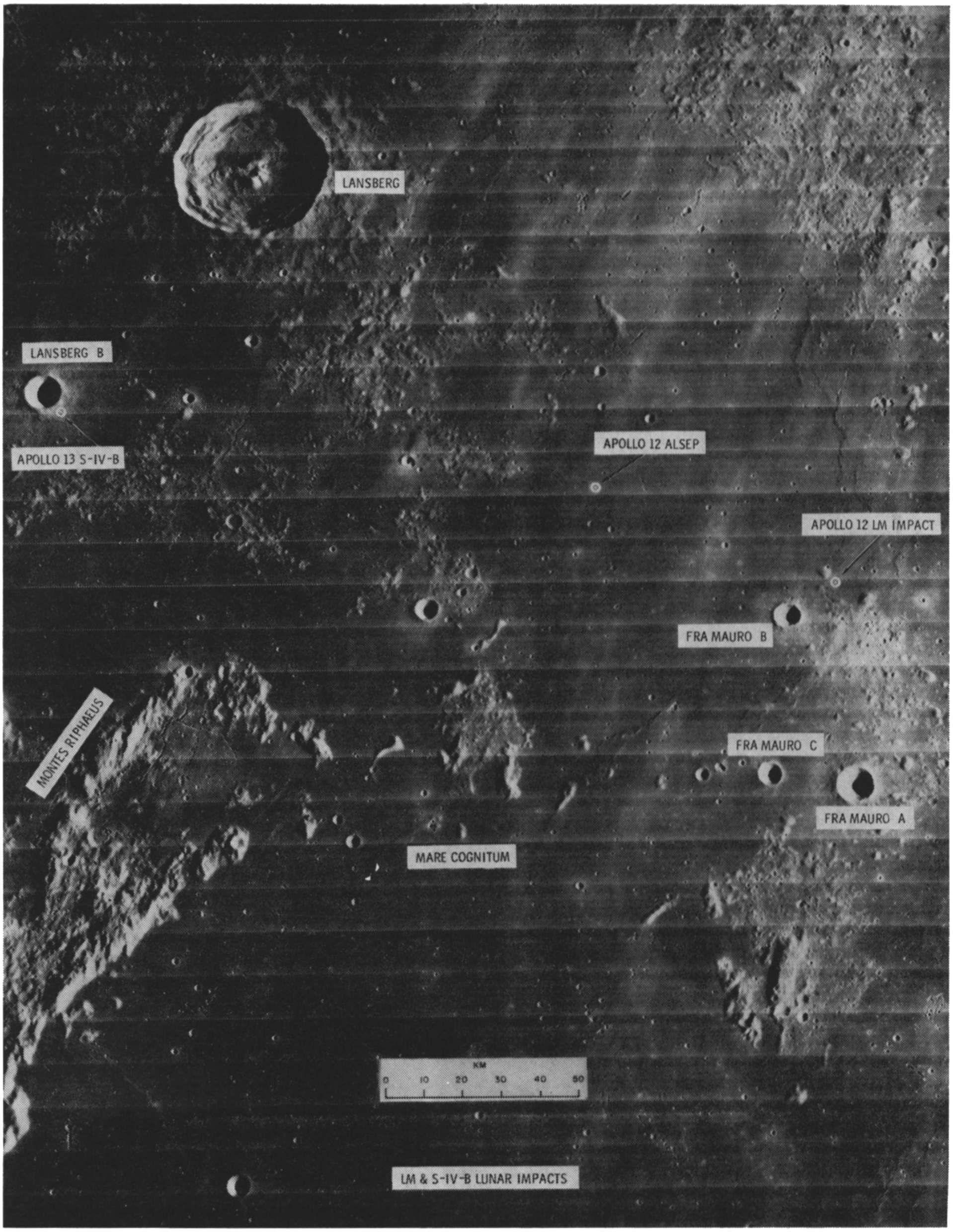

Fig. 2. Orbiter photograph of the lunar surface, showing the locations of the Apollo 12 seismic station and the points of impact of the Apollo 12 LM ascent stage and the Apollo 13 S-IVB. The region shown is in the southwestern edge of Oceanus Procellarum.

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a lava flood early in the history of the Moon. Several separate episodes of flooding may have occurred. The lava layer is believed to be between 0 and 2 km thick in this region [6].

2. Description of Lunar Seismic Signals

The vertical component signals from the artificial impacts and those from the two largest natural events recorded thus far are shown on a compressed time scale in Figure 3. For comparison, the signal from a missile impact recorded at White Sands,

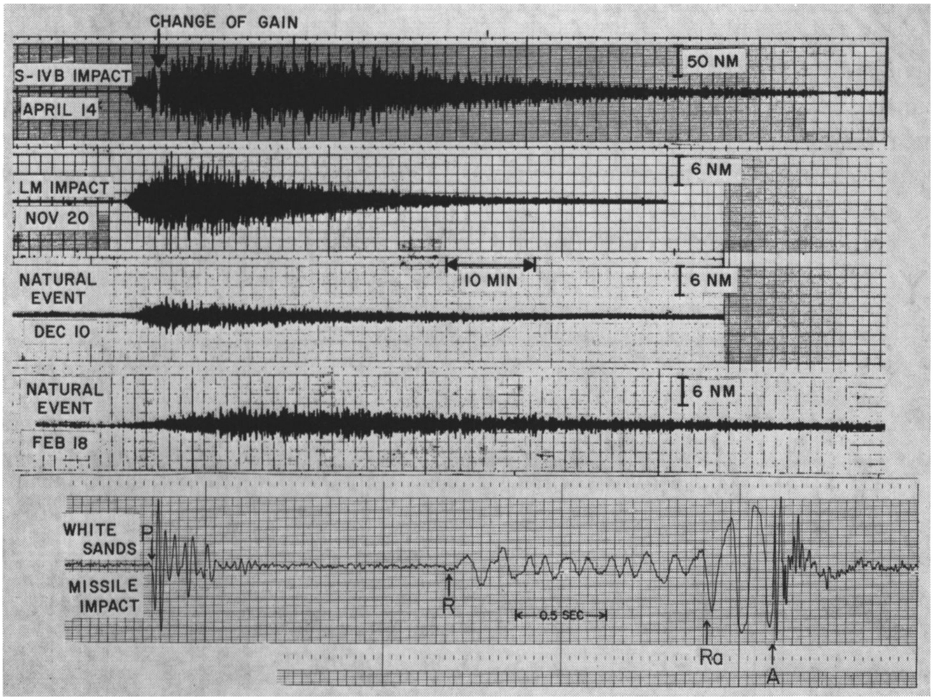

Fig. 3. Signals from the LM and S-IVB impacts, and from two of the largest natural events recorded to date. All signals recorded on the long-period vertical component seismometer. A record of the seismic signal from a missile impact recorded at the White Sands Missile Range is also shown for comparison. For the White Sands record: $P = P$ wave; $R =$ Rayleigh wave; $A =$ atmospheric acoustic arrival; distance = 1.5 km; kinetic energy $1.5\ (10)^{15}$ erg.

New Mexico, is also shown on a greatly expanded time scale – it would appear as a single 'blip' if on the same time scale used for the others. The signals from all of these lunar events are clearly similar in character, but, as a class, they are quite different from the White Sands missile impact signal or from typical earthquake signals.

The lunar signals are complex. They have very long durations, and their amplitudes increase and decrease gradually. For any selected event, the signal envelopes for all

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three components are remarkably similar, but there is remarkably little detailed correlation between any two components of ground motion (Figure 4). Compressional and shear wave arrivals have been identified in the early parts of the wave trains, but they are much less distinct than in normal earthquake recordings. The predominant

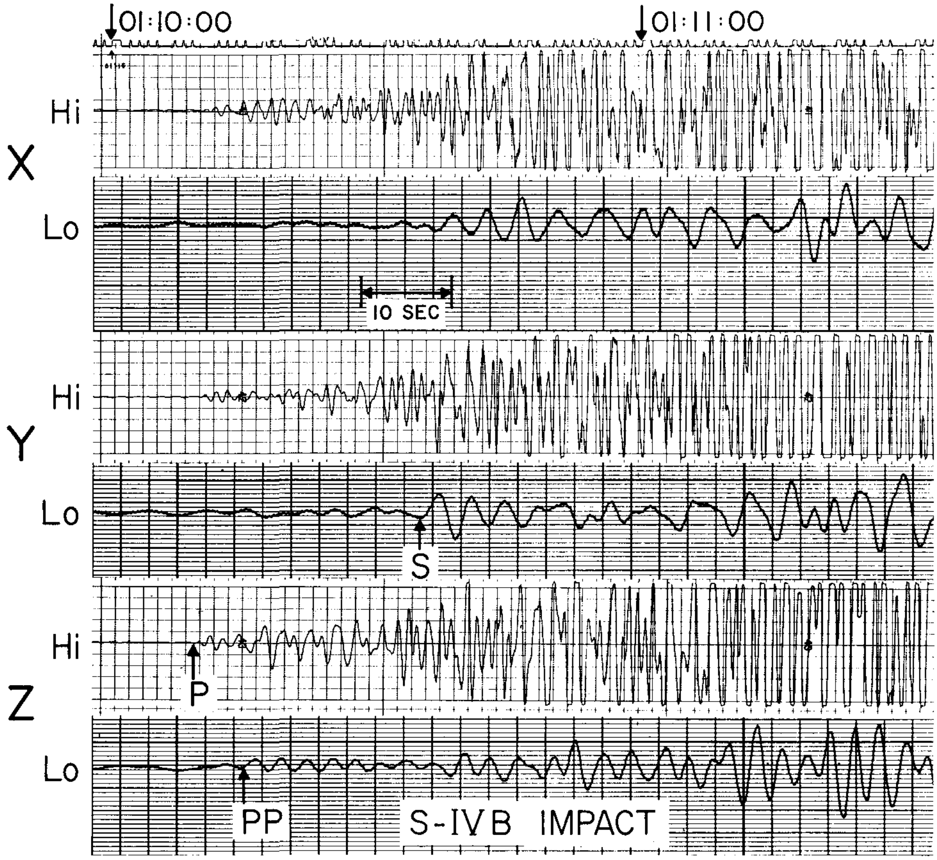

Fig. 4. Initial portion of the S-IVB impact signal on an expanded time scale, with high-pass filtering (Hi) to emphasize the *P* wave, and low-pass filtering (Lo) to emphasize the *PP* and *S* waves. *X* and *Y* are horizontal component seismometers, and *Z* is the vertical component. The *X* and *Y* components are approximately transverse and radial, respectively, for the S-IVB impact.

signal frequency remains relatively constant throughout a given signal, but differs somewhat for different types of events.

A number of mechanisms are under consideration by various workers for explaining these confusing details, and when the questions are finally resolved, we will gain much valuable information about gradients of velocity, stratification, scattering processes, etc., in addition to estimates of epicentral distance. But, in the meantime, we can ignore details and relate duration of the signal (amplitudes being normalized) to distance of source in a purely empirical way. A similar empirical correlation of duration with distance works out rather well for terrestrial explosion seismology if we avoid obvious radical variations in type of terrane; or, in earthquake seismology, if we exclude deep focus shocks and avoid the prolongations introduced by the sea water in transoceanic propagation. Which power of distance should be used for scaling depends on knowledge of mechanism, but we should be reasonably safe in interpolating between, or extrapolating only moderately beyond, our calibration impacts at about 70 and 140 km. According to this simple system, the distance for LM is least, those for S-IVB and the December 10 event are intermediate, and the February 18 event is farthest of the events illustrated in Figure 3.

In Figure 4, the beginning of the S-IVB impact signal is shown on an expanded time scale, using low and high pass filters for three components of motion. Signals corresponding to the arrival of compressional waves (P) and shear waves (S) (waves which travel through the body of the Moon), have been identified on the seismic records. Our ultimate hope for determining azimuth of the source (with records from only one station) depends on establishing phase relations between the three components for each type of wave.

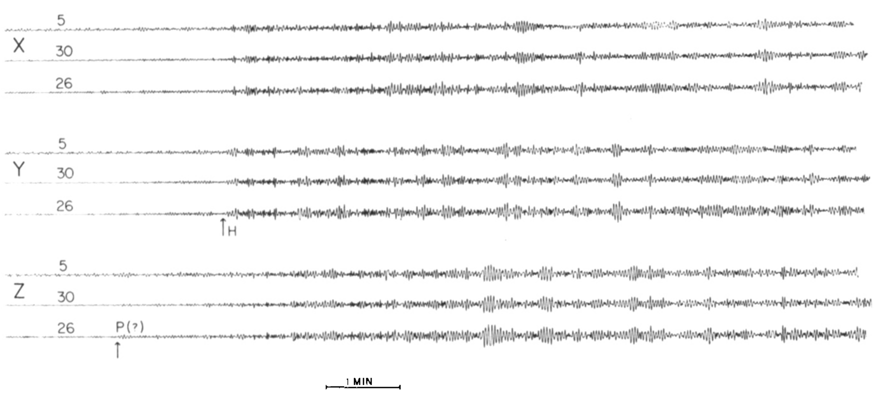

Fig. 5. Seismograms showing 3 of the matching seismic events (category A signals). The events shown occurred at the following times: event 5, 13.27 h, January 6, 1970; event 26, 14:30 h, April 26, 1970; event 30, 13:09 h, May 23, 1970.

More detailed analysis of the 35 largest seismic signals of natural origin (out of our collection of over 250 events) has revealed that some of them bear a striking resemblance to one another. Among them are 14 signals, to be designated as Category A signals, which match closely in nearly every detail of the record for the entire duration of the signal. Whatever may have generated the Category A signals happened at least 14 times in 7 months in exactly the same way and at the same place. The signals differ among themselves only in magnitude. Such repetition of detail suggests that these events are moonquakes rather than impacts. According to our rough scale of distance, this epicenter was about 200 km away from the seismograph. Seismologists have found

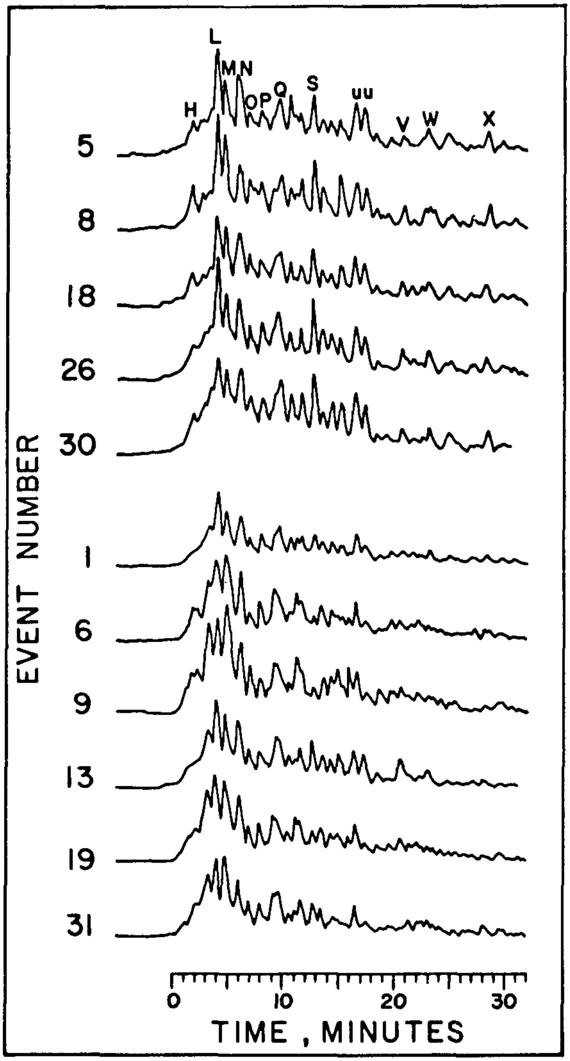

Fig. 6. Plots of signal energy versus time for 11 Category A events. The energy plots represent the running average of ground displacement squared (filtered, low-pass, corner period of 32 sec). The marking of phases (except for *H* and *L*) may be considered as arbitrary, and for purposes of intercomparison only. A1 signals are in the upper part of the figure; A2 in the lower.

a few places on Earth from which repeated earthquakes generate seismograms as similar to each other as are these moonquakes.

An additional set of 8 signals (Category B signals) are similar in many ways to those of Category A. We consider them to be the same type as Category A – i.e., moonquakes, but at various other epicenters. Three of the Category B events (B1) match one another closely and are considered to represent repetitive moonquakes from a second epicenter. All of the Category A and B signals have spectra which are relatively flat in contrast to the remaining 13 signals (Category C), which have well-developed broad spectral maxima near 1 Hz.

Seismograms for three of the matching A events, chosen as having nearly equal amplitudes, are shown in Figure 5. While the identity between these signals for any one of the components of ground motion is clear, the lack of obvious similarities among the 3 components of motion is equally striking and difficult to interpret. The most significant phases identifiable in the Category A signals are here labeled *P* and *H*. The phase marked *P* is considered to be the direct compressional *P* wave from the source, but we must admit the possibility that weak forerunners may be present. The

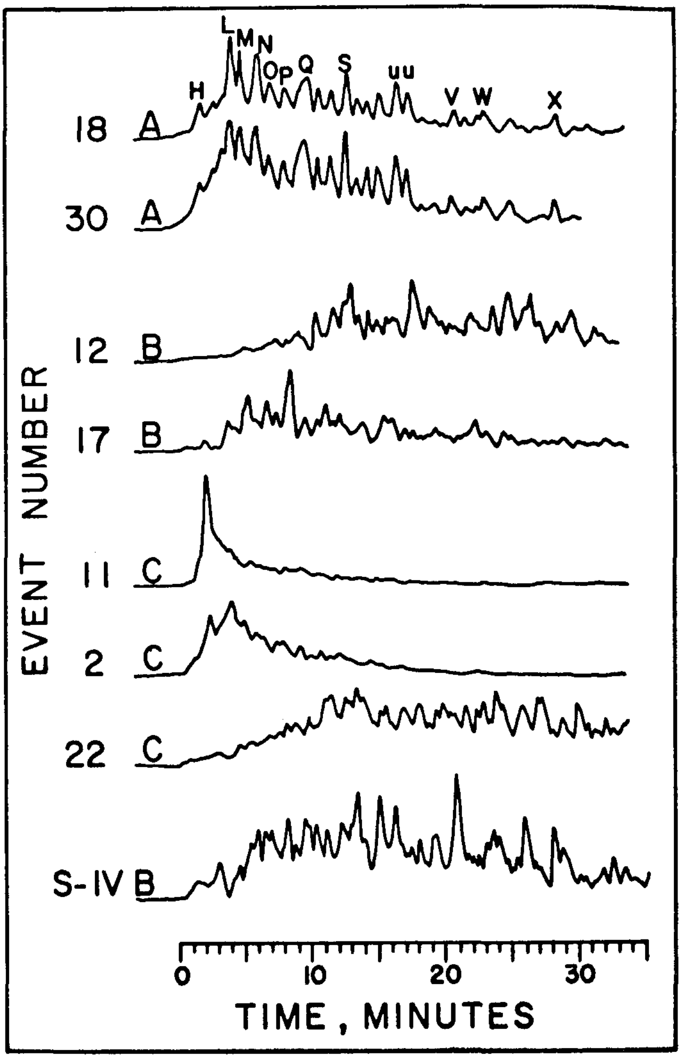

Fig. 7. Plots of signal energy versus time for typical Category A, B, and C events.

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H phase is most likely the beginning of the surface waves. The 14 Category A events were identified among the 35 largest signals. A study to identify the Category A events, which appear to be present among the smaller signals, is being made.

The striking similarity among the Category A events is further evidenced by comparing the signal energies as a function of time through the wave train. Energy plots for 11 of the Category A events are shown in Figure 6. By comparing small details of the energy plots, we are able to divide the 14 events into two sub-sets, A1 and A2, but the differences are small and the general features of all 14 signals match quite closely. The contrast between Category A, B, and C signals is shown by comparison of typical energy plots in Figure 7. It appears that plots of this type are valuable for classifying the lunar seismic signals and selecting those suitable for detailed study.

3. Sources of Lunar Seismic Signals

Two sources of lunar seismic energy are expected: (1) moonquakes, i.e., seismic energy release caused by sudden dislocations within the Moon, or volcanic activity; and (2) meteoroid impacts.

Times of occurrence of the various types of seismic signals and times of perigee are shown in Figure 8. All of the Category A events occur within 3 days of perigee. At least one event is detected at each perigee. In 5 of the 7 perigee periods included in the data, the first event, belonging to sub-set A1, is followed by one or two A2 events at an interval from 2.5 to 4.5 d. In the remaining two perigee crossings, only one A1 event is observed at each crossing. Five of the 8 Category B events occur near perigee, another near apogee, and the remaining two at intermediate times. The

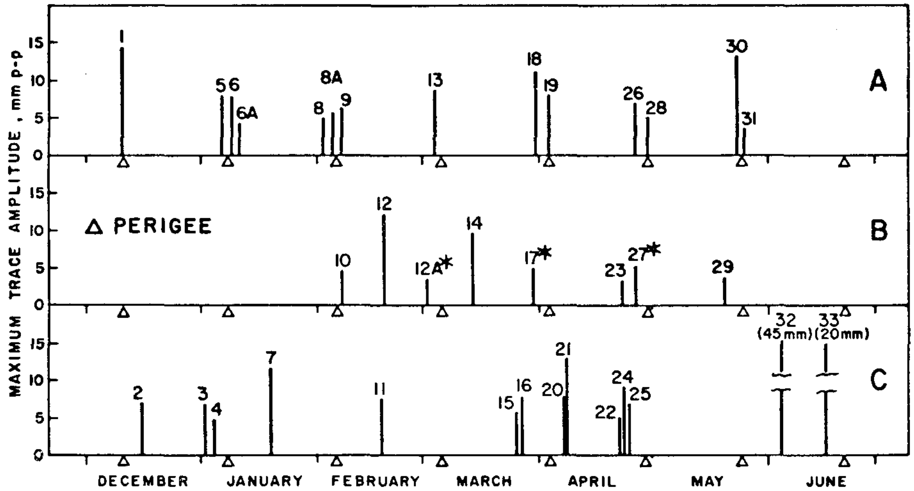

Fig. 8. Times of occurrence of seismic activity recorded at the Apollo 12 seismic station. Note that signals which may belong to Category A have not yet been analyzed for the period corresponding to the last perigee crossing.

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occurrence of the high-frequency (Category C) events does not appear to be related to perigee.

Events which produce virtually identical seismic signals, as those of Category A, must have a common point of origin and a common focal mechanism. Meteoroid impacts can be eliminated as a possible source owing to the very low probability that they could be concentrated at the same point on the lunar surface and would occur in association with perigee. The clear relationship between the occurrence of the low-frequency events and perigee strongly supports the conclusion that these events are moonquakes induced by tidal strains which reach maximum values at perigee. The identification of three categories of matching events A1, A2, B1, suggests that there may be three distinct foci of repeating moonquakes. However, the considerable similarities between signals of the A and B categories may mean that the foci are fairly close together.

By comparison between the matching signals and the artificial impact signals, and a careful analysis of phase relations between the three components illustrated in Figures 3, 4, and 5, the source of the Category A signals is tentatively placed roughly 200 km southeast of the Apollo 12 station. It is of interest that this location is within the crater Fra Mauro near a prominent set of rills and also near the intended landing site for the Apollo 14 mission.

Seismologists are well aware of the uncertainty in estimating epicentral distance and azimuth with data from a single seismic station and when the identification of most of the recorded phases is uncertain. But, given calibrations corresponding to the two lunar impacts, rough estimates of distances of seismic sources can be obtained from empirical record patterns and the durations of the signals. Even more serious uncertainty must be recognized in deductions of azimuth until the cause of signal prolongation and of weak correlation of phase for the three components (probably a single cause for both) is understood more fully.

The pattern of moonquake activity is strikingly similar to the pattern of occurrence of lunar transient events as summarized by Middlehurst [7] and quite naturally suggests a possible relationship. Middlehurst [7], Cameron and Gilheany [8], Moore [9], and others have shown that lunar transient events are sighted most commonly at times of perigee. The frequency of transient events plotted relative to the anomalistic period of the Moon, as given by Middlehurst, is shown in Figure 9. Such events have been described by many astronomers as sudden appearances of bluish or reddish color or simply brightening, or, in some cases, a short-term obscuration of a given locality on the Moon. These events most frequently occur near edges of maria, in dark flat-floored craters, near lunar domes and sinous rills, and near dark-haloed craters. The appearance of many of these features suggests volcanic origin. Thus, it has been suggested that the lunar transient events are produced by sudden venting of gases from the lunar interior. Many of the sightings are related to the crater Aristarchus. In the region of the Apollo 12 seismic station, lunar transient events have been reported from the craters Ptolemaeus, Alphonsus, Copernicus, Gassendi, and Lansberg. Except for Lansberg (distance = 120 km), these sites are much farther than our present estimate

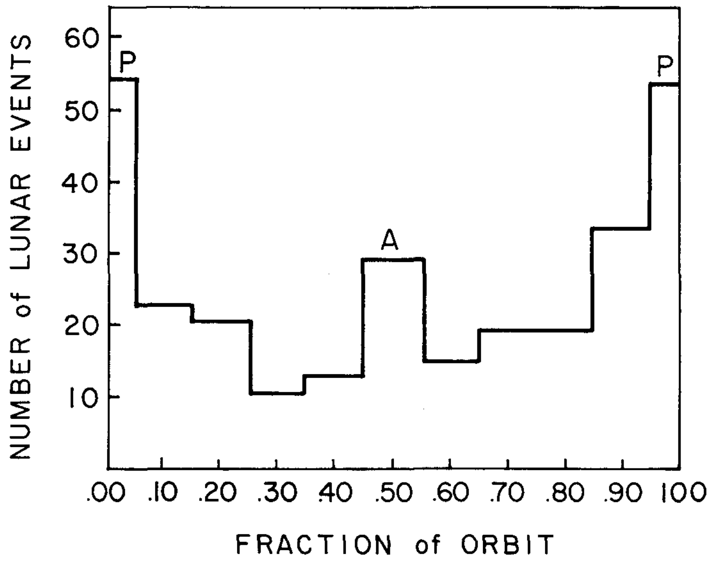

Fig. 9. Frequency of occurrence of lunar transient events relative to the anomalistic month P = perigee; A = apogee; (from Middlehurst, [1]).

of the distance to the source of the moonquakes. No transient events have been reported for the crater Fra Mauro. Nevertheless, the association of lunar transient events and seismic activity with times of perigee suggests that both phenomena are related to tidal strain. Perhaps a tidally-induced dislocation which radiates seismic waves may also permit the escape of gases along the same zone of weakness.

The fact that the events of each category (A1, A2, B1) are identical in polarity, implies that the source mechanism is a progressive one and not one which periodically reverses direction. Evidence of large scale displacements resulting from tectonic strains are very rare (many observers would say absent) on the Moon, but this does not exclude the possibility of localized strain accumulations associated, for example, with large impacts, or secular temperature changes of the lunar interior. If this interpretation is correct, zones of weakness in the Apollo 12 region along which such slippage occurs may indeed be limited to a few points.

A review of the Apollo 11 seismic data has shown that the three seismic signals recorded both on the long period and short period seismometers also occurred at times of perigee. Two perigee crossings were included in the 21 days of operation of the Apollo 11 station. Therefore, it is probable that tidally-triggered seismic events occur at other locations on the lunar surface, but are not detected owing to the greater distances of these locations from the seismic stations.

From the similarity between the spectra and character of the artificial impact signals and the Category C signals, it is likely that the latter are produced by meteoroid impacts. On the assumption that prolongation of all lunar seismic signals results from some sort of scattering that can be treated with the diffusion Equation [2], we can estimate the distance between the seismic station and the source by variation of parameters in that equation, to give the best fit to the signal envelope as described below. On this basis, the recorded impacts occurred at distances as great as 200 km. Adjusting signal amplitudes for differences in range, we find that seven events with seismic energy equal to, or greater than, that generated by the LM impact have been recorded during seven months of operation at the Apollo 12 site, or an average rate of 1 per month. Since the LM struck the surface at a very shallow angle, most of its kinetic energy was retained by fragments of the LM leaving the initial impact point. By comparison with the seismic energy generated by the S-IVB impact, we estimate that only 20 per cent of the LM kinetic energy was given up to the lunar surface at the point of initial contact. Assuming a meteoroid velocity of 20 km/sec, the LM kinetic energy lost at initial impact is equivalent to that of a meteoroid with a mass of 3.5 kg. Thus, we estimate on the above assumptions, that 1 meteoroid impact per month, of mass 3.5 kg or greater, has occurred in the region of the Apollo 12 station at ranges up to 200 km. If we take 30 km/sec as the average meteoroid impact velocity, the meteoroid mass with kinetic energy equal to the LM impact is 1.6 kg.

The predicted number of impacts per year in a circle of 200 km radius, based upon the flux estimate of Hawkins [10] for meteoroids in the kilogram range, is 0.6 per month for masses of 3.5 kg and larger, and 1.3 per month for masses of 1.6 kg and larger. Thus, our observed rate of 1 per month is in approximate agreement with Hawkins' estimate.

As additional data become available, particularly some observations from a station in the highlands area, we expect to be able to establish much more definitive bounds on meteoroid flux in near-lunar space.

4. Lunar Structure and Dynamics

A. STRUCTURE OF MARIA

Information on the structure of a medium through which seismic waves propagate derives primarily from the measurement of the velocities and spectral properties (frequencies and amplitudes) of the various types of seismic waves transmitted through the medium. With data from a single station only, the time and location of the source must be known. At present, these data are available only for the two artificial impacts.

Independent information is provided by measurement of seismic velocities on returned lunar samples. These measurements are made by placing the rock sample under pressure and measuring the speed of ultrasonic waves passing through it. Increasing pressure is equivalent to increasing depth within the Moon. In this way, seismic velocities as a function of depth within the Moon may be estimated. Experimental results of this type have been reported for the Apollo 11 samples by Kanamori *et al.* [11] and Schreiber *et al.* [12]. The samples used are basalts which contain numerous voids and microfractures. The intrinsic densities of these samples range between 3.3 and 3.4 gm/cc. These measurements predict very low surface velocities and a very rapid increase in velocity with depth in the upper 20 km of the Moon to between 4.8 and 5.6 km/sec. The low surface velocities result from the presence of open pores and microfractures in the samples. The rapid increase in velocity with depth is produced by the closing of cracks and voids under pressure. Complete consolidation of rock material from this may not occur under the reduced lunar gravity until depths of at least 20 km have been reached. Considerations of this type may be very misleading unless allowance is made for the effect of compaction by impact in a zone below those in which melting, lithification, crushing and excavation occur.

If the compaction by meteoroid impact is ignored, the travel time curves for various types of seismic waves can be constructed from the laboratory data. Body wave travel times as a function of distance between the source (impact point) and the receiver (seismic station) are plotted in Figure 10. The travel times of seismic waves from the impacts are also indicated. The nature of the various seismic waves shown in this figure were described earlier. Suffice it to say that the seismic velocities predicted from laboratory measurements and those observed from the impacts are in reasonably good agreement.

The curves based upon laboratory measurements are applicable only if the outer 20 to 40 km of Oceanus Procellarum consists of rock material similar to the crystalline rocks used in the measurements. The degree of agreement between the velocities of seismic waves from the impacts and those measured in the laboratory indicate that this may be the case. Based upon the impact signals, we can also state that an important seismic discontinuity equivalent to the base of the crust on Earth cannot exist in the outer 20 km of the mare.

Phase changes, expected according to some petrologic models at depths greater than those for which information is provided by the available seismic data, cannot be investigated until events at greater distances are recorded.

Several lines of evidence suggest that the elevation of the highland areas indicates that such areas are formed from a layer of low density rock (probably anorthosite) approximately 10 km in thickness [13]. Test of this hypothesis will be possible when a seismic station is established in the highland area. At the present, we have no assurance that our results are relevant to any part of the lunar surface beyond the maria.

Additional information on lunar structure can be gained by analysis of the extended trains of waves which follow the early body wave arrivals, as described earlier. We refer to these trains as lunar seismic reverberations. Any explanation of the reverberations must take into account that (1) surface waves are expected to make an important contribution to seismic signals generated by impacts or shallow moonquakes; (2) the duration of the reverberation is unusually long; (3) the signal frequency is relatively constant throughout a wave train, but is not the same for all signals; (4) the envelope of any one of the signals is nearly identical on all three components; (5) there is little detailed correlation in phase or in amplitude between any two components of ground motion. The hypothesis which presently appears to explain all of these observations most satisfactorily is that the lunar seismic reverberations result from intense

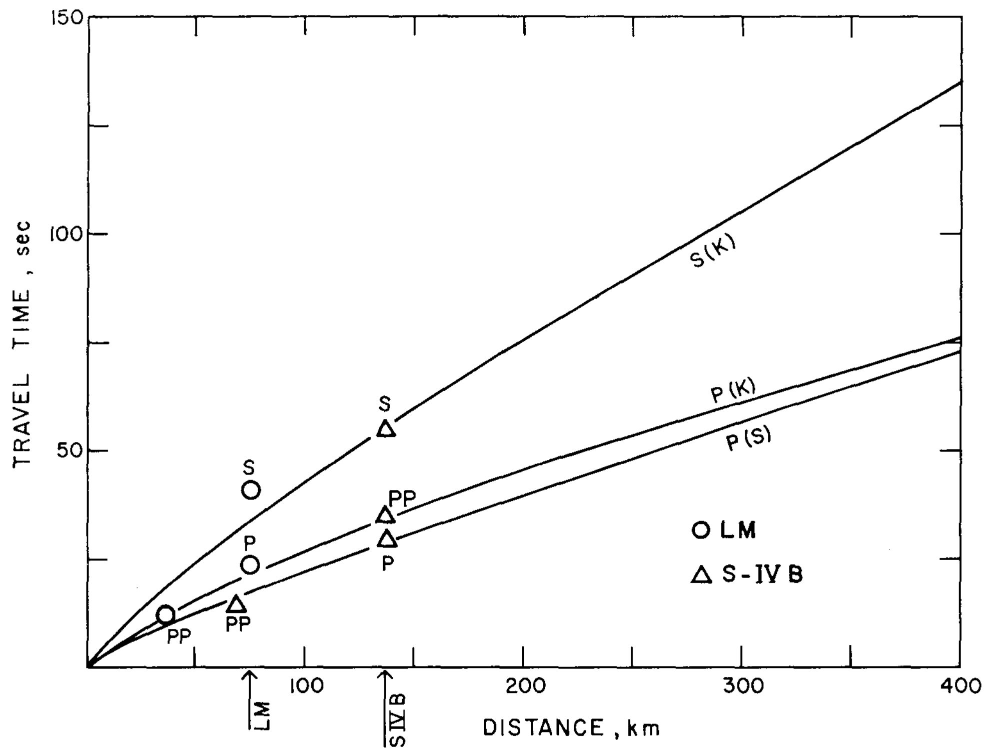

Fig. 10. Travel times of seismic waves from the lunar impact signals. Solid curves are derived from laboratory measurements of seismic velocities on returned lunar samples. $P(S)$ = compressional wave velocities measured for a lunar rock sample by Schreiber *et al.* [12]; $P[K]$, $S[K]$ = compressional and shear wave velocities measured for a lunar rock sample by Kanamori *et al.* [11].

scattering (and possibly from some dispersion) of surface waves in a medium with very low absorption of seismic energy.

If seismic wave scattering is sufficiently intense, certain aspects of the phenomenon may properly be described by diffusion theory. By application of the laws of diffusion to seismic wave propagation, we found [2] that an accurate fit to the envelope of the seismic signal can be obtained with proper selection of the coefficient for diffusion and absorption of the medium. These results imply that the absorption of seismic waves must be at least one order of magnitude lower for the lunar material than is typically observed for Earth crustal materials [2]. If the explanation in terms of diffusion is correct, the value of the diffusion constant required to obtain a fit to the data implies heterogeneity within the lunar material on a scale from several hundred meters, or less, to several kilometers.

That the outer shell of the Moon might be highly heterogeneous is not surprising in view of the extreme age of the surface. Meteoroid bombardment would probably have shattered any massive lunar material to depths approaching 50 km. Also, the lava which was sampled from Oceanus Procellarum is reported to have a very low viscosity and a high thermal coefficient of expansion [14]. A lava with these properties would be expected to fracture extensively after solidification and possibly to form extensive networks of lava tubes within the flow. Alternately, the heterogeneity might simply be characteristic of the outer shell of a body formed by accretion of cold particles.

The extremely low absorption of seismic waves in the lunar material is probably explained by the nearly complete absence of fluids in this material, and possibly by low temperatures in the upper few kilometers of the Moon.

B. DYNAMICS OF THE MOON

As discussed above, it now appears certain that seismic energy release, related to lunar tides, does occur within the Moon. However, the magnitudes of these events and their numbers are small in comparison to the seismic activity which would be recorded by an equivalent seismic station on Earth. The magnitudes of the natural events, based upon the Richter magnitude scale normally used in earthquake studies, is between 1 and 2. Such earthquakes are very small; in fact, barely perceptible by persons in the immediate vicinity of the epicenter. On earth, more than 1 million earthquakes of this magnitude occur each year. If the seismicity of the Moon were equivalent to that of the Earth, and assuming that such events could be detected to ranges of 300 km on the Moon and were uniformly distributed in the outer shell of the Moon, we could expect to record several hundred events of the magnitude of the Category A events in seven months. Between 10 and 100 events of magnitude equal to the S-IVB impact also would have been recorded in this period. No events comparable to the S-IVB impact have been recorded.

Correlation of seismic events with tidal parameters on Earth is very weak – some investigators have claimed it to be negligible. The principal reasons to expect a stronger correlation on the Moon are (1) the tidal effect is an order of magnitude larger, (2) absence of other transient stresses which could also serve as triggers – atmospheric pressure changes, stress waves from large quakes, surges in the hydrosphere, etc., and (3) the time interval between maxima of tidal stress are more than an order of magnitude greater, permitting greater accumulation of tectonic stress.

Clearly, the duration of recording, the area covered, and the type of terrane studied by lunar seismic stations are much too small to provide a basis for generalization. But the results suggest that lunar seismicity in the regions of the Apollo 11 and 12 seismic stations is far below that of the Earth. As was suspected from the extreme rarity of morphological features attributable to tectonic action, the outer shell of the Moon is far more stable than typical regions of the Earth.

5. Summary and Conclusions

(1) Seismic signals from approximately 250 natural events and from two man-made impacts have been recorded during seven months of operation of the two seismic stations installed during Apollo missions 11 and 12. The natural seismic events are

moonquakes and meteoroid impacts. With few exceptions, moonquakes occur at times of perigee. Thus, internal lunar seismic activity appears to be induced by tidal stress, the correlation being considerably stronger than that reported by Middlehurst and others for transient lunar events. The low level of detectable seismic activity relative to that on Earth and the presence of mascons, suggests that the outer shell of the Moon is quite rigid and tectonically stable compared with the outer regions of the Earth.

(2) Both the natural events and artificial impacts produce reverberations of unusually long duration. The lunar seismic reverberations may be explained as resulting from scattering of surface waves in the outer 2 to 3 km of the Moon. Absorption of seismic energy in this material is extremely low compared with typical Earth crustal materials. This may be a consequence of the absence of fluids in the near-surface materials, or of low temperature, or a combination of these factors. The precise nature of the heterogeneity is unknown, but to explain scattering of the observed wave lenghts, separations between structural or compositional discontinuities must range from several hundred meters, or less, to several kilometers.

The seismic data indicate that the lunar maria consist of materials of very low velocity near the surface, with velocities increasing rapidly with depth to 5 to 6 km/sec (for compressional waves) at a depth of approximately 20 km. This result is consistent with velocities predicted from laboratory measurements on returned lunar samples. This result implies that rocks collected at the surface have the same elastic properties under appropriate pressures as the material which forms the upper 20 km of the maria. We cannot infer from this that the basaltic rock material found at the surface actually extends to at least 20 km, although this is a strong possibility. We can state that no major discontinuity equivalent to the Mohorovičic discontinuity, which defines the base of the crust on earth, can exist in the upper 20 km of the maria. Discontinuities at greater depths, expected from phase changes, cannot be investigated until seismic events at greater distances are observed. Booster impacts from future missions are expected to satisfy this requirement.

(3) Suggested shallower layered structure of the highlands can be investigated when a seismic station is established in the highlands. The explanation of the elevation of the highlands, based on isostatic compensation, implies that extensive petrologic differentiation has occurred within the Moon. But, the melting which led to this differentiation apparently was not sufficient to produce a large dense central core, since the Moon's moments of inertia are very nearly equal to that of a homogeneous sphere. The suggestion that only a superficial layer was melted is a target for investigation when more distant events are recorded.

(4) Meteoroid flux in the kilogram mass range, inferred from the seismic measurements, is in approximate agreement with the flux estimate of Hawkins [10].

(5) Presently, at least, the outer shell of the Moon appears to be relatively cold and tectonically stable.

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